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TEST ANALYSIS REPORT/EVALUATION OF FORACS I 3-D SOFTWARE

PC Wilfong

VERAC Incorporated

8 April 1982

Prepared for
Naval Ocean Systems Center
SACS/FORACS Division

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R-023-82

8 April 1982

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ACKNOWLEDGEMENTS

This report describes the evaluation of the software system developed by VERAC for acoustic tracking of undersea vessels. The effort was performed under Contract No. N66001-81-C-0228. A number of VERAC personnel participated in the evaluation effort. Dr. Donald R. Vander Stoep, as Program Manager, and Paul Wilfong, as Principal Investigator, were responsible for specifying requirement definitions, algorithm and software design, and evaluation procedures. Dr. Leonard Gross and Mr. Edwin Schnaath contributed to the design and coding of several components of the system.

Several FORACS and NUWES personnel contributed to the evaluation effort. Mr. James Treadway, Mr. Paul Moore, and Mr. Ron Gillis were instrumental in assisting with the effort. Finally, range personnel from San Clemente and St. Croix, respectively John Elliot and John Williams, were especially helpful in coordinating with the effort.

Report preparation was handled by Ms. Maureen O'Connor, whose expertise made this report possible.



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1.0 INTRODUCTION

A 3-D undersea tracking filter has been developed using optimal estimation techniques. The implementation has centered upon the use of the Square Root Information Filter/Smother (SRIF/S), which provides computational efficiency and enhanced numerical stability along with the accuracy associated with optimal estimation. Recent effort to evaluate the capabilities of the filter and associated smother will be described in this report. The evaluation activity has involved the following three-stage approach:

- Reduction of data from surface vehicles tracked using the FORACS I 3D system. This is a synchronous system.
- Implementation of the SRIF/S on the Sperry Univac V77 mini-computer at FORACS I.
- Reduction of data from surface vehicles tracked using the FORACS II 3D system. This is an asynchronous system.

These three stages collectively provide for all evaluation criteria necessary to demonstrate the operability and validity of the SRIF/S software as described in the remainder of this report.

The rest of this report is divided into 7 sections. Section 2 outlines the test goals and the approach taken to meet these goals. Section 3 describes the SRIF/S design for this activity. Section 4 discusses the pre-processor component of the data reduction system. Sections 5 and 6 detail the evaluation effort carried out to meet the goals set forth in Section 2. Finally, the results of the evaluation effort are summarized in Section 7.

2.0 EVALUATION GOALS AND APPROACH

The 3D tracking SRIF/S has evolved as a general purpose software system which includes a special simulation capability, providing a means for code checkout and modeling analysis without the need for actual test data. SRIF/S evaluation had proceeded using this capability prior to the current effort, contributing substantially to initial development. During this period, code development and checkout was accomplished using VERAC's in-house minicomputer system, a PDP-11/34.

To carry forward the SRIF/S development, two major goals were necessary:

- (1) Implement the SRIF/S on a NOSC supplied minicomputer system used for 3D tracking, to establish system constraints due to computational and I/O burden and to evaluate in a general sense the operability of the SRIF/S in such an environment.
- (2) Reduce actual 3D test data to establish filter and smoother performance, using an independent reference when possible.

These specific goals provided the guidelines necessary to achieve a comprehensive evaluation of the 3D tracking and post test processing software in a realistic environment with independent monitoring. The first goal was addressed specifically within the context of a separate contract (F33657-81-G-2009), and is mentioned here only briefly for completeness. The second goal is discussed fully in this report.

Two sources of undersea tracking data were available. The FORACS I San Clemente range system provided time-of-travel measurements; i.e., measurements consisting of the time from a pinger pulse to its reception at a hydrophone. This method of undersea tracking is referred to as "synchronous". The FORACS II St. Croix range provided measurements consisting of arrival time at a hydrophone. This type of tracking is referred to as "asynchronous". Thus, the SRIF'S capability of handling either asynchronous or synchronous data could be demonstrated.

The FORACS II data also had associated with it optical (theodolite) data which could be used to establish a separate vehicle track for comparison, thus providing the necessary independent reference for evaluation of the SRIF/S.

3.0 MODEL DEFINITION

This section describes the particular implementation of the SRIF/S used in the evaluation activity. Specifically, the state vector structure and measurement models are given. For a detailed discussion of the SRIF/S implementation, see Reference 2.

3.1 State Vector

The filter state vector is fixed order, and is composed of the 12 components listed in Table 3-1. These may be written as:

$$\underline{x}^t = (B_T, p^t, B_{vp}, \underline{s}_x^t, \underline{s}_y^t, \underline{s}_z^t).$$

B_T represents a time bias, to model the delta time offset which must be added to the estimated "ping start time" to yield the true "ping start time". It is modeled as a random walk process to account for oscillator instability.

Table 3-1. Tracking Filter State Vector

B_T	Time Bias
P_1	Water Dynamics Parameter for Hydrophone 1
P_2	Water Dynamics Parameter for Hydrophone 2
P_3	Water Dynamics Parameter for Hydrophone 3
P_4	Water Dynamics Parameter for Hydrophone 4
B_{vp}	Sound Velocity Profile Correction Factor
X	Boat X Coordinate (North)
\dot{X}	Boat X Velocity
Y	Boat Y Coordinate (East)
\dot{Y}	Boat Y Velocity
Z	Boat Z Coordinate (Down)
\dot{Z}	Boat Z Velocity

$p^t = (P_1, P_2, P_3, P_4)$ represents water dynamic errors, to model changes in the liquid medium through which the sound path from the boat transducer to the hydrophone must travel. P_i is associated with hydrophone i ($i = 1, \dots, 4$), and is applied in conjunction with B_{vp} as a multiplicative correction factor to the Sound Velocity Profile (SVP); this process is described below. The water dynamic parameters are used to model changes in the water medium caused by spatial differences in the environment, mixing, etc. They are modeled as Markov processes which are spatially correlated.

B_{vp} , the SVP correction factor, is also modeled as a spatially correlated Markov process. It is applied, in conjunction with the P_i parameters, as a multiplicative correction factor to compensate for errors due to incomplete knowledge of the SVP, as described in Section 3.2. The values used for the correlation constants and for the steady state variance can be altered easily to fit test conditions.

The coordinate axis states "s" include position and velocity:

$$\begin{bmatrix} s_x^t \\ s_y^t \\ s_z^t \end{bmatrix} = \begin{bmatrix} x, \dot{x} \\ y, \dot{y} \\ z, \dot{z} \end{bmatrix}$$

The velocity states are modeled as random walk processes whose noise "strength" variances can be altered easily to fit test conditions and which are to be used to model vehicle movement during a test operation.

3.2 Filter Measurement Model

The k^{th} set of hydrophone measurements are given as:

$$y_k = T_k + B_T \left(\frac{\pi}{1 + B_{vp} + P_i} \right) + n_i$$

where B_T , B_{VP} , and P_i are given in Table 3-1, and n_i is the i^{th} hydrophone instrument noise value (jitter). TT is the ping travel time computed using the input Sound Velocity Profile (SVP), as described in Reference 1. T_k is an estimate of the ping start time either made available along with the measurement data (in the synchronous case) or computed as a pre-processing step (in the asynchronous case); it is assumed that the interpinging time $T_k - T_{k-1}$ is constant.

The nonzero elements of the measurement sensitivity vector \underline{H} are given by the following for the i^{th} hydrophone:

$$\frac{\partial y_i}{\partial B_T} = 1$$

$$\frac{\partial y_i}{\partial P_i} = -TT * K^2$$

$$\frac{\partial y_i}{\partial B_{VP}} = -TT * K^2$$

$$\frac{\partial y_i}{\partial X} = S * (X - H_{Xi}) * K$$

$$\frac{\partial y_i}{\partial Y} = S * (Y - H_{Yi}) * K$$

$$\frac{\partial y_i}{\partial Z} = \frac{-\cos(\theta_B) * K}{V_B}$$

where

$$K = \frac{1}{(1 + B_{VP} + P_i)}$$

$$S = \text{Snell's constant}$$

$$\theta_B = \text{angle of sound path at the boat transducer}$$

V_B = velocity of sound at the boat transducer

H_{xi} = X coordinate of hydrophone

H_{yi} = Y coordinate of hydrophone.

The derivations of these partial derivatives are given in Reference 1.

4.0 PRE-PROCESSING

Two important problems must be solved when dealing with real data from an undersea tracking range. The first is that to provide a data processing capability for many different ranges, a method must be developed to deal with many different data formats, since each range will record the tracking data in a different manner. The second is that undersea tracking data is usually interleaved in the following sense; the order measurements are recorded may not reflect the actual order they were produced. This is due to the (relatively) long propagation time of sound under water over long distances; if the pinger data rate is high enough, the closest hydrophone will receive pings from two or more pulses before the farthest hydrophone receives the first pulse.

The best method for dealing with these problems from a software engineering standpoint is via pre-processing programs which are separate from the main SRIF/S programs. In this fashion, modularity is maintained and flexibility is enhanced.

Figure 4-1 illustrates the processing stages carried out in the pre-processor.

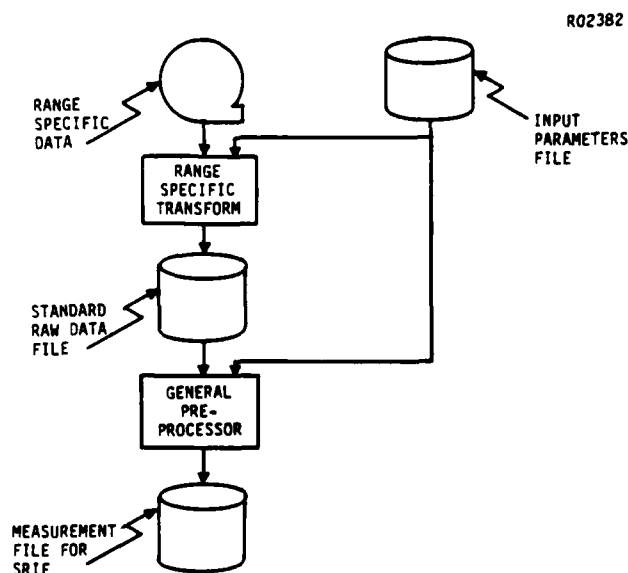


Figure 4-1. Pre-Processor Data Flow

Data provided by the test range is transformed via a "range specific" processor to a standard raw data file. The "input parameters" file specifies the time interval and hydrophone selection list. One such "stage one" program is provided for each range; for the current effort, for example, two stage one pre-processors were developed, one for San Clemente and one for St. Croix.

The "stage two" (general) pre-processor is used to de-interleave the raw data and provide pulse start estimates (either directly from the raw data for the synchronous case, or computed for the asynchronous case). The data is formatted and tagged with identification and validity flags for input to the SRIF. The design of the stage two pre-processor is described in Reference 3.

5.0 SYNCHRONOUS MODE EVALUATION

The SRIF/S software has been designed to accommodate data from a synchronous or an asynchronous tracking system. In this section, results from using synchronous data from the San Clemente Island range are presented.

Raw tracking measurements recorded on magnetic tape during tests of the San Clemente 3D tracking system were obtained. The format and content of these tapes are given in detail in Reference 3. As discussed in Section 4, a pre-processor component was used to deinterleave the raw data in preparation for reduction by the SRIF/S. In addition, certain difficulties in the data were discovered which led to additional effort in preparing for use in the SRIF/S; these difficulties and their solutions are also documented in Reference 3.

The pre-processor was used to extract a segment of data from a tape created December 1980. Approximately 35 seconds of the data was extracted. The integrity of this data set was verified, to ensure the validity of the measurements. (Other data tapes were found to contain inconsistent measurements).

The tracking filter and smoother were used to obtain coordinate estimates and sigmas for the test vehicle. Figure 5-1 shows an overall view of the vehicle track for the data set used, with an expanded view in Figure 5-2. The SRIF/S was configured for synchronous tracking by setting the initial value for the B_T sigma to a negligibly small value, and the actual initial B_T estimate to zero. As can be seen by examining the measurement model in Section 3.2, this corresponds to the situation in which the pulse start time is known, which is the case for synchronous tracking.

The results of the SRIF/S processing are given in Figures 5-1 through 5-6. The first two are plots of the X and Y estimates as calculated by the smoother. The third is of Z, where the positive ordinate axis indicates down. Thus the smoother estimate of the boat pinger position is approximately 2 feet below sea level for the data

set, which corresponds closely to the expected average depth taking into account pinger depth and tide. A slight bias exists in the Z estimate which can be attributed to mis-modelling of the Sound Velocity Profile, since it was unavailable for the test date. Nevertheless, the bias is well within the 1-sigma uncertainty estimates generated for Z by the smoother, indicating the validity of the position estimates.

Figures 5-4 and 5-5 are plots of the X position and velocity sigma estimates, respectively. The results in Y and Z were similar. These plots indicate the good accuracy (approximately ± 2.5 feet in position) of the estimates for the track selected. Although estimate uncertainties are geometry dependent, they should not vary too greatly for a synchronous system when the tracked object is within the hydrophone grid.

The velocity sigma plot in Figure 5-5 shows the behavior which is typical of smoother sigmas in general. The endpoint behavior reflects loss of data at that location. Close examination of position sigma plots (e.g., Figure 5-4) reveals similar behavior.

Finally, Figure 5-6 shows an example of the filter residual plots for the hydrophone measurements. These are normalized by the hydrophone noise (jitter) value used. As can be seen, these residuals are well-behaved, and lead to increased confidences in the validity of the SRIF/S estimates.

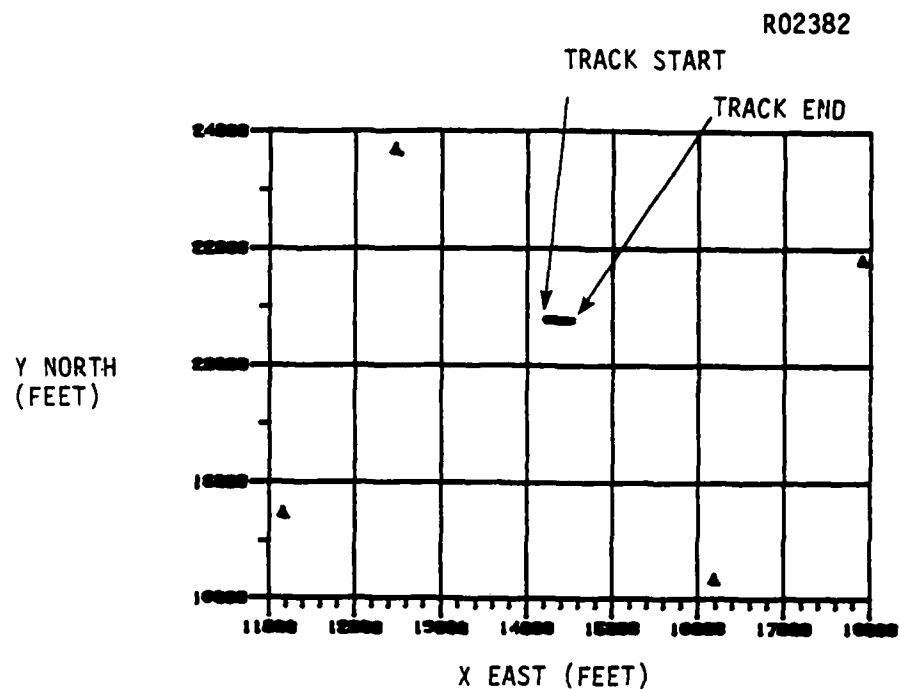


Figure 5-1. Boat Track: Triangles Indicate Hydrophone Positions

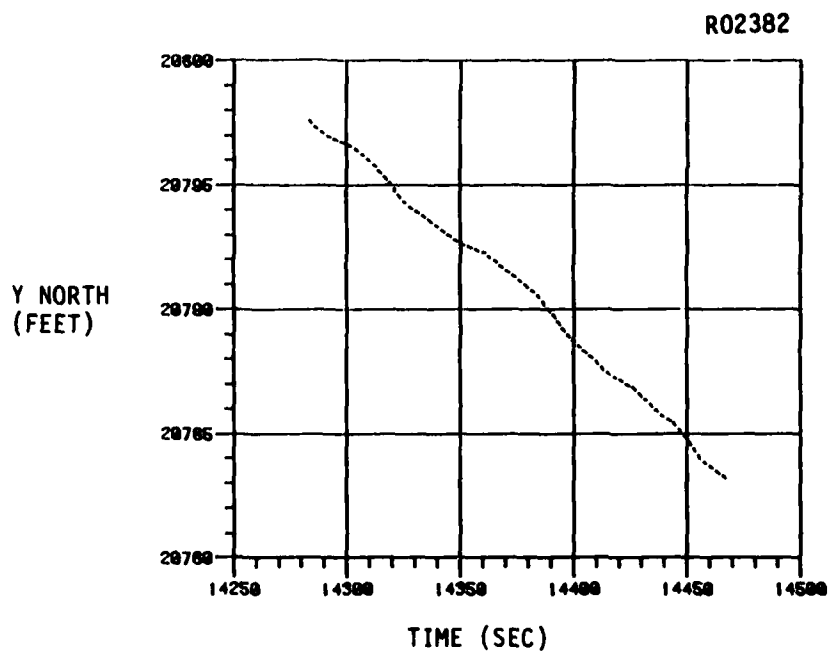


Figure 5-2. Boat Track: Expanded Scale (from Smoother)

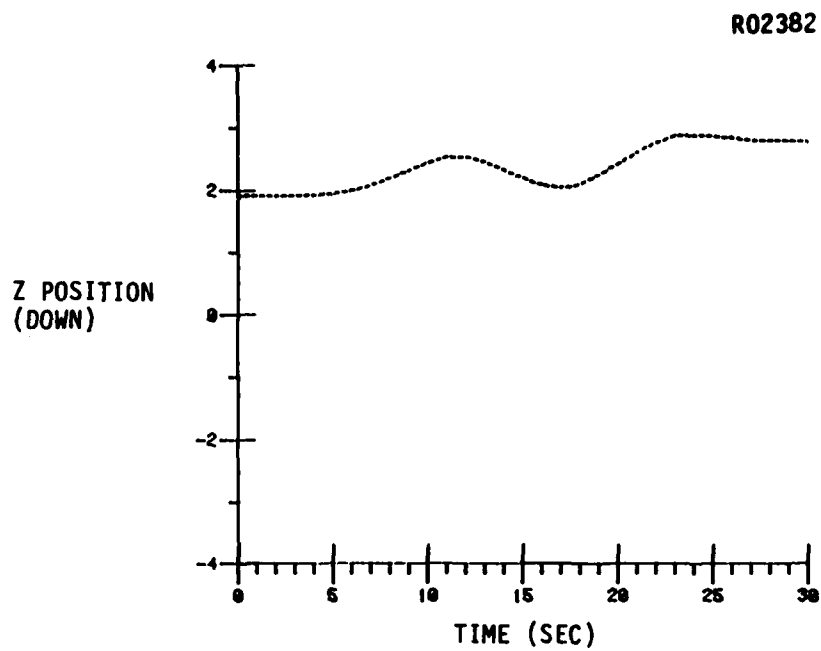


Figure 5-3. Smoother Z Position

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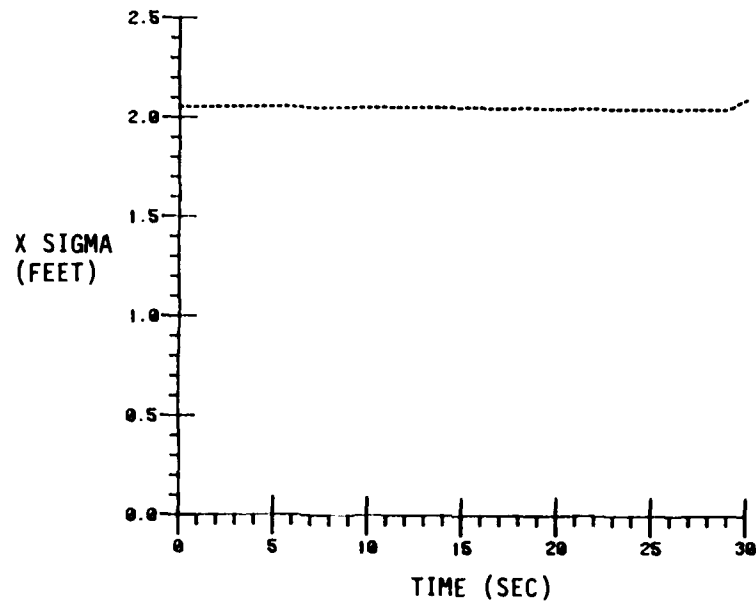


Figure 5-4. Smoother X Position 1-Sigma Bound

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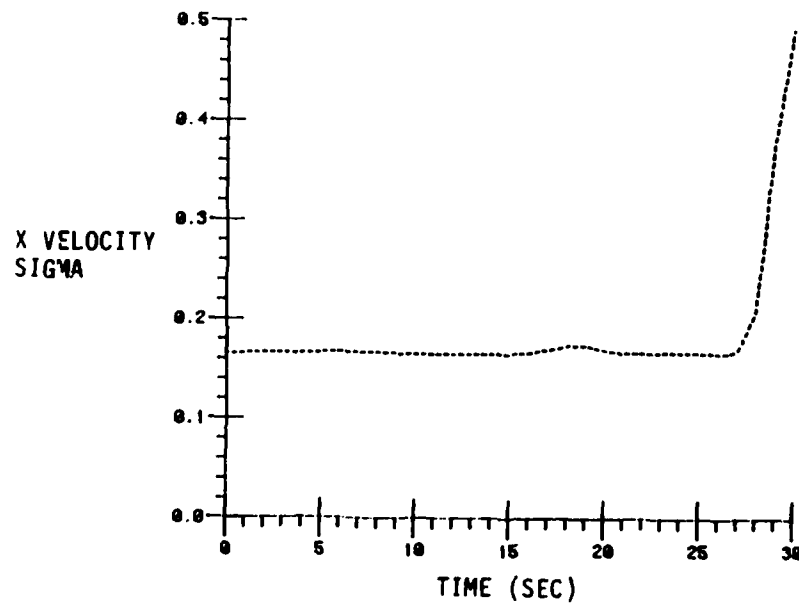


Figure 5-5. Smoother X Velocity 1-Sigma Bound

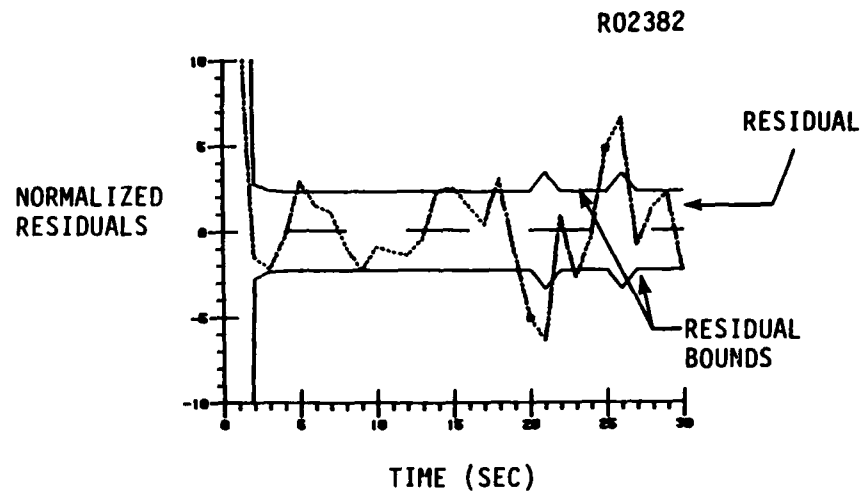


Figure 5-6. Filter Normalized Residual Plot
Asterisks Indicate Rejected Measurements

6.0 ASYNCHRONOUS MODE EVALUATION

In this section, results from using asynchronous data from the St. Croix range are presented.

Raw tracking measurements recorded on magnetic tape during a test on the St. Croix range were supplied by St. Croix personnel, along with the information necessary to make use of the data. The range system on St. Croix, described in Reference 5, is quite sophisticated. As discussed in Section 4, a pre-processor component was used to deinterleave the raw data in preparation for use in the SRIF/S. As the discussion in Section 3 shows, the SRIF/S is currently capable of reducing data from only four hydrophones. The St. Croix range is capable of tracking an object with more than four hydrophones. Thus the pre-processor component for this data selected measurements from only four of the available tracking hydrophones.

A number of runs were available which included simultaneous optical coverage. Of these, the first and third runs were reduced. Figure 6-1a shows the scenario for these runs. The first was used to examine reduction in an adverse geometry; the vehicle was outside the grid of four hydrophones used for tracking, as shown in Figure 6-1b. Run 3 was used to examine SRIF/S behavior in a more advantageous geometry (Figure 6-1c).

As mentioned above, these runs had simultaneous optical coverage, consisting of bearing measurements taken from three shore theodolites at approximately 50 second intervals. These bearing measurements were combined to form optical fixes for the vehicle using Stansfield's method, which is described in Reference 7. This method provided a reference for comparison to the SRIF/S results. It was assumed that the theodolite measurements had uncertainties of 30 arc seconds (1σ).

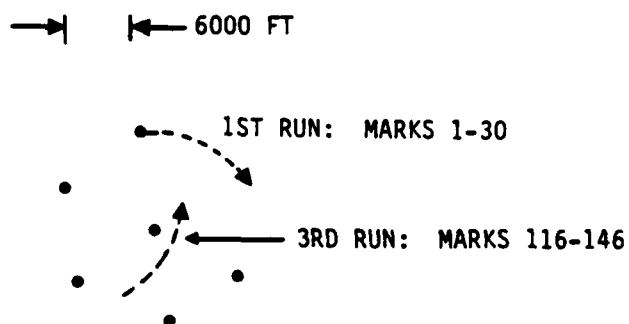


Figure 6-1a. Test Runs -- Hydrophone Locations are Indicated by •



Figure 6-1b. Test Run Number 1



Figure 6-1c. Test Run Number 3

A significant difficulty with the optical reference is that it is not synchronized with the hydrophone data. The measurements may be up to one second apart. For the test runs examined, the vehicles are moving at approximately 6 ft/sec, so that the optical vs. acoustic results can conceivably differ by up to 6 feet due to the lack of synchronization. Nevertheless, the optical reference provides an extremely valuable method for evaluating the SRIF/S results.

The SRIF/S was configured to asynchronous tracking by setting the initial value for the B_T sigma to .5 second. At first, only data for the first two marks from Run Number 1 was reduced (approximately 46 seconds), to examine modeling assumptions.

Figures 6-2 and 6-3 show plots of smoother residuals over the first two marks for Run Number 1. The residuals for hydrophone 2 are well-behaved, while those for hydrophone 1 exhibit numerous dropouts. Examining Figure 6-1b shows that hydrophone 2 is closest to the vehicle, suggesting that consistent data cannot be obtained beyond a range of 6000 ft. The smoother residual plots for other hydrophones seem to support this hypothesis.

Figures 6-4 and 6-5 show the smoother sigmas for vertical and north position estimates for the first two marks of Run Number 1. Initially, the values for these sigmas seemed excessive, based on experience with the synchronous data. Further analysis, however, showed that the sigmas indicated are realistic given the short time interval processed and the location of the vehicle relative to the hydrophones. The large sigmas reflect the poor geometry of the scenario. Over a longer run, as the vessel moves into more advantageous areas, the filter sigmas will tend to become smaller. Then, as the smoother works backwards, it can use the information from the filter for the good areas to improve the estimate sigmas in the poor areas. Figures 6-6 and 6-7 illustrate this. These are plots of the vertical and north sigmas for data covering a much longer period of time (approximately 1400 seconds; the first 30 marks of Run Number 1). The upper plot corresponds to the filter a posteriori sigma estimate, which gradually improves as time

progresses. The smoother, working backward, can take advantage of the information obtained at the end of the run to improve estimate sigmas at the beginning of the run, as is shown by the lower sigma plots.

A significant modeling assumption in the design as described in Section 3.2 was that the pulse inter-ping time was precisely known. This turned out to be untrue, as was shown by the behavior of the B_T state in the filter. In actuality, when a value of 1 second was used as the assumed inter-ping time, the B_T estimates exhibited a distinct ramp behavior, indicating that the inter-ping time was not precisely 1 second. Based on this observation, this parameter was tuned until acceptable behavior was achieved. It was subsequently verified by FORACS personnel that interping timing cannot be established to the assumed value.

The final verification of the SRIF/S system was accomplished by comparing the optical and acoustic track results. Figures 6-8 and 6-9 show typical results from this type of comparison. These are plots of the differences in X and Y between the optical and acoustic track points, at the theodolite marks. Also, the expected sigmas for these differences are plotted. These are the Root-Sum-Squared combinations of the sigma estimates from the SRIF/S and the Stansfield fixes.

As shown in these sample plots, the optical reference indicates that the SRIF/S estimates are very good, and reasonably behaved with respect to the sigma estimates. The apparent bias in these plots can be attributed to lack of synchronization between the acoustic and optical data, as discussed previously.

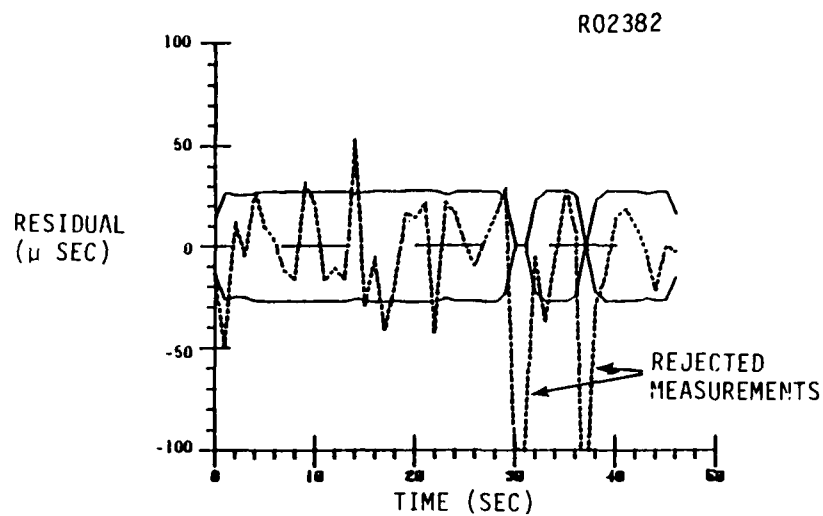


Figure 6-2. Hydrophone 2 Smoothed Residuals (Run Number 1)

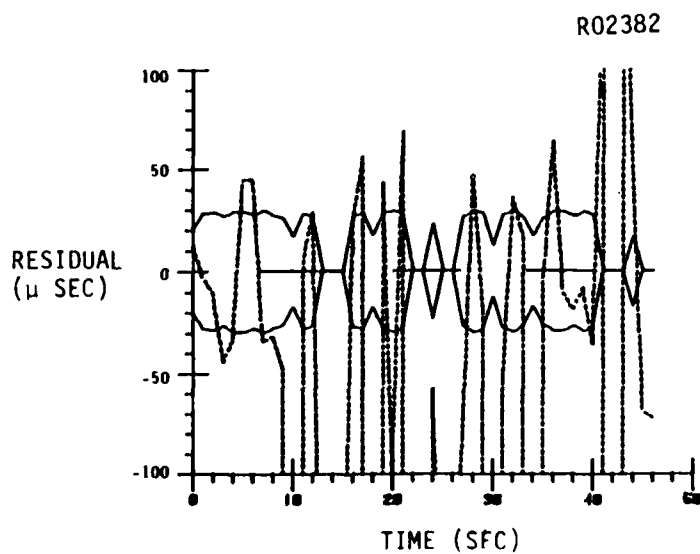


Figure 6-3. Hydrophone 1 Smoothed Residuals (Run Number 1)

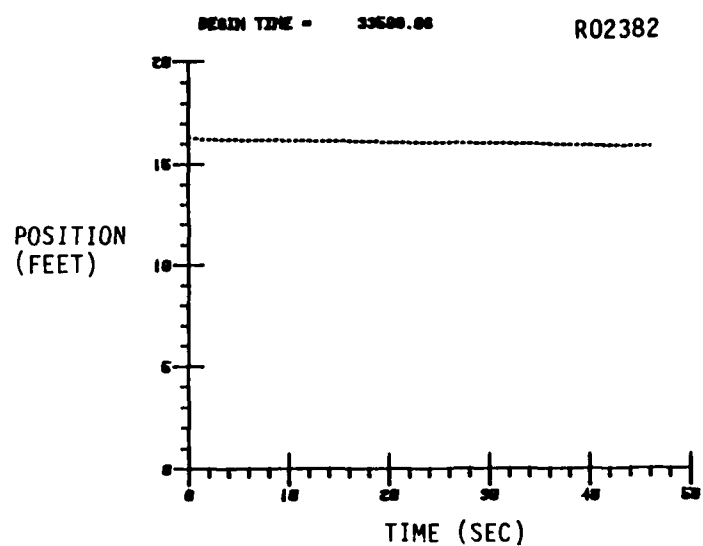


Figure 6-4. Smoother Vertical Position Sigma
(Error Standard Deviation)

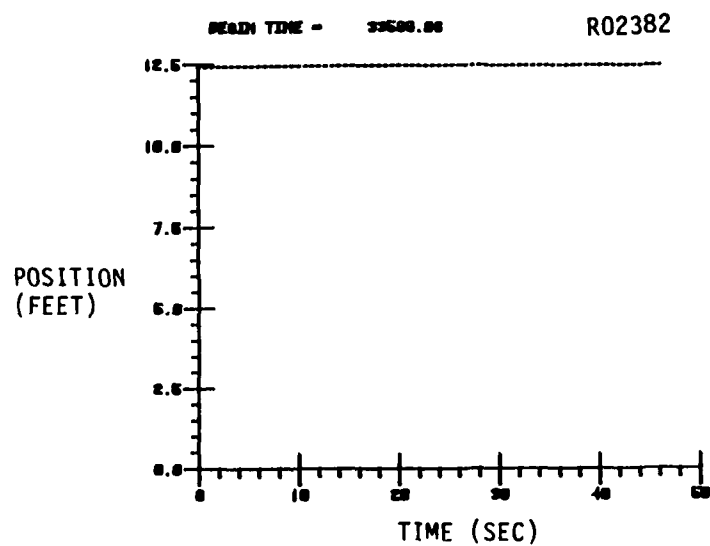


Figure 6-5. Smoother North Position Sigma

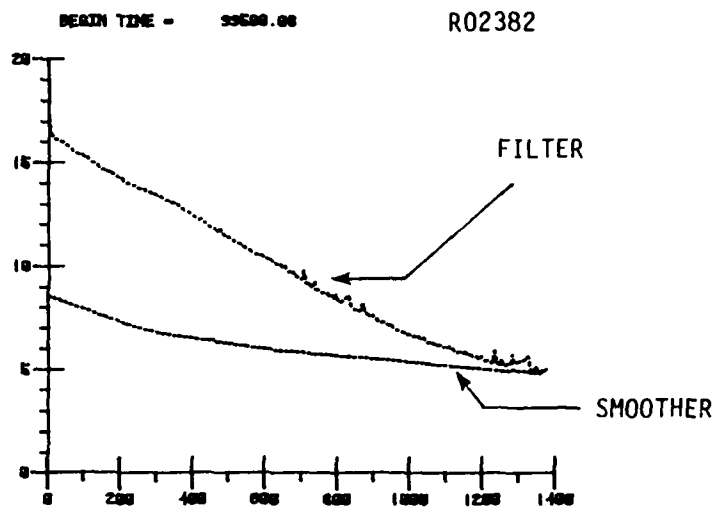


Figure 6-6. Vertical Sigma Plots (Run Number 1)

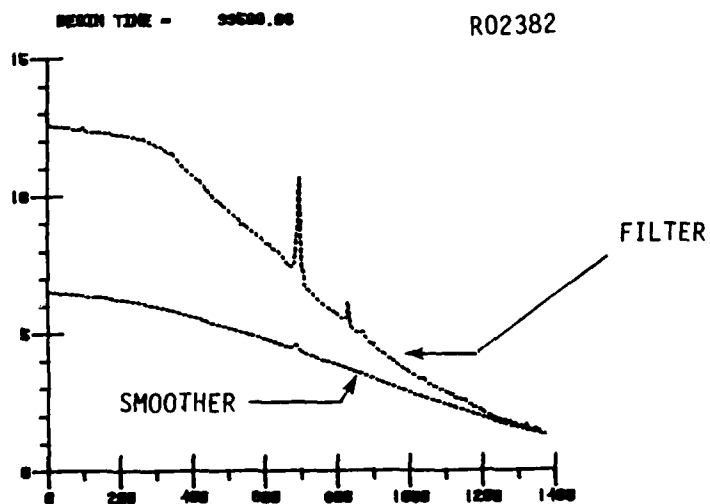


Figure 6-7. North Sigma Plots (Run Number 1)

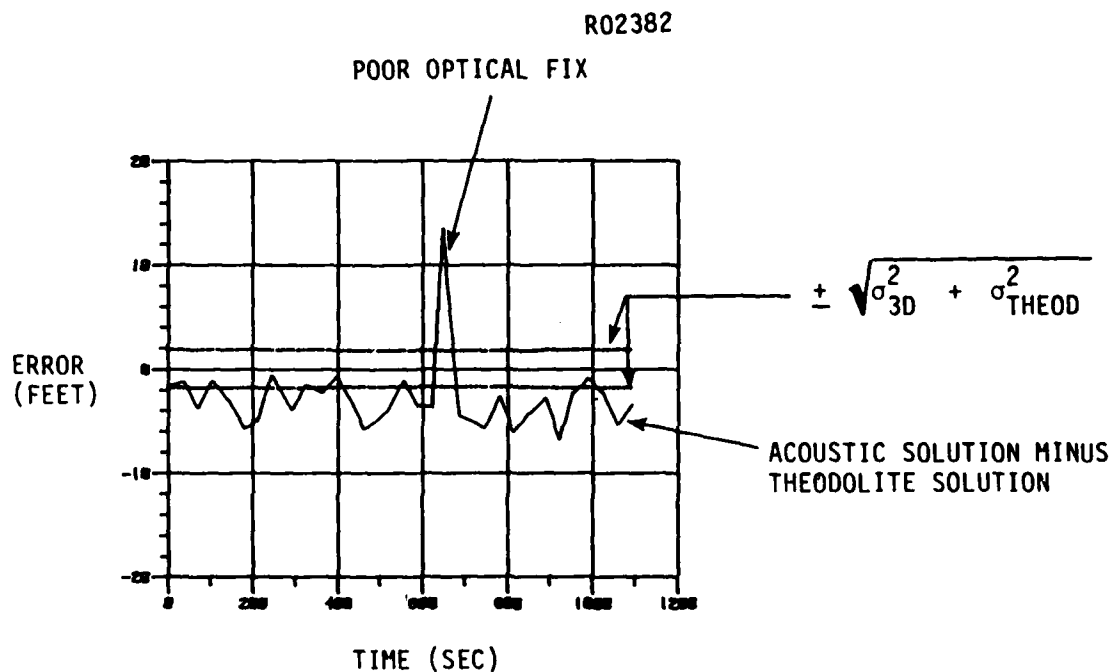


Figure 6-8. North Position Error (Smoother: Run Number 3)

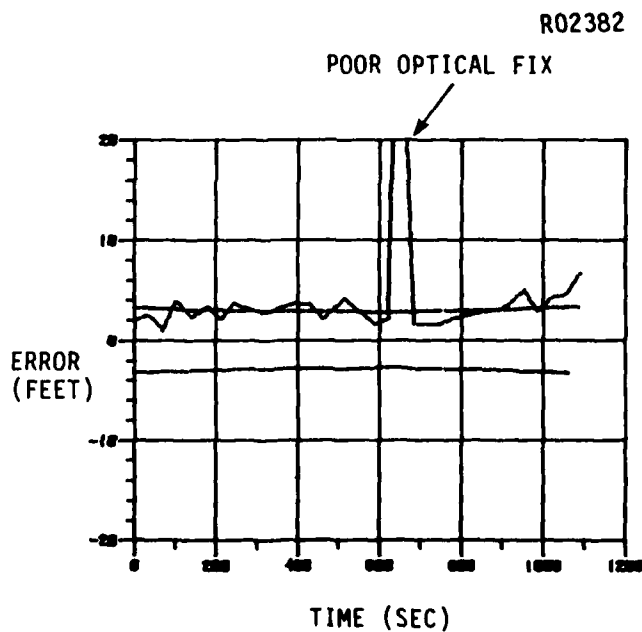


Figure 6-9. East Position Error (Smoother: Run Number 3)

7.0 SUMMARY AND CONCLUSIONS

This report documents the verification procedures carried out to provide comprehensive evaluation of the SRIF/S 3D tracking and post test processing software. The procedures used have permitted rigorous evaluation of the software in a realistic environment with independent test monitoring by utilizing an optical reference for comparison. The asynchronous and synchronous capabilities of the tracking software have been verified by reducing data from both types of systems.

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